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EXPERIMENTAL STUDY ON VELOCITY AND WAVE PROFILES DURING AIR-WATER FLOW IN HORIZONTAL CHANNELS

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Abstract. *This paper presents an experimental vector velocity field for liquid phase during smooth stratified flows in horizontal channel with internal diameter of 44.6 mm and the shear stress profile. Experiments for determination of velocity profiles of liquid phase flow were performed for air-water flow. The experiments comprise superficial gas and liquid velocities between* 0,0747 *and* 0,1067 *m/s, and* 0,0769 *and* 0,1321 *m/s, respectively. The velocity profiles were determined in the central plane of test section with the non-intrusive technique Particle Image Velocimetry – PIV.*

Keywords: *stratified flow, horizontal channels, particle image velocimetry, shear stress profile, velocity profiles.*

1. NOMENCLATURE

x relative to x axis [m]
y relative to y axis [m]
$\overline{U}$ average velocity [m/s]
$\overline{V}$ average velocity [m/s]
u' velocity fluctuation [m/s]
v' velocity fluctuation [m/s]
ρ phase density [kg/m³]
τ shear stress [Pa]
μ viscosity [Pa.s]

2. INTRODUCTION

Multiphase flows correspond to the flow of two or more immiscible phases, which may be of the same substance in different phases, or of different and immiscible substances. Two-phase flow is the simplest case of multiphase flow, corresponding to the flow of two-phases, which may be liquid-liquid, gas-liquid and particle-fluid. The flow patterns of the two-phase flows can be characterized by the spatial distribution of the phases, which depends on the channel orientation and geometry, fluid properties, flow velocities, and so on. Even though the experimental investigation of flow patterns has been reported in several studies, such as in Baker (1954), Taitel and Dukler (1976), Kattan et al. (1998), Wojtan (2005), the phenomena occurring during stratified flow are not still completely understood.

The separate flow patterns are characterized by the simultaneous flow of the phases separated by a single and continuous interface (Mishima and Hibiki, 2010), such as the case of stratified and annular patterns. The stratified flows can be sub-classified as smooth and wavy according to the geometric structure of the interface, as indicated by Taitel and Dukler (1976), and the transition between the two patterns was modelled by these authors based on the Kelvin-Helmholtz interfacial stability analysis.

Although Taitel and Dukler (1976) proposal for this transition contributed to the understanding of both flow patterns, many studies in this area need to be developed in order to obtain more information about the mechanisms that lead to the transition between smooth and wavy stratified, as wavy stratified and slug or annular.

Therefore, the objective of this study is to contribute to the research field by providing reliable experimental results for the velocity profile in the liquid phase. The velocity profiles for the liquid phase were determined with the use of PIV (Particle Image Velocimetry).

3. MATERIALS AND METHODS

3.1 Experimental apparatus

The experimental apparatus, used during the experimental campaign is available in the facilities of the National Institute of Metrology Quality and Technology under the direction of the Division of Metrology in Fluid Dynamics, Rio de Janeiro State, Brazil.

The experimental bench consists in a closed circuit of water, and compressing and conditioning air system. The water flows from a reservoir with capacity of 500 liters propelled by a centrifugal pump Dancor model PF-17 with nominal power of 1.47 kW, installed in parallel with a pump Grundfos model CHIE2-50 power 0.78kW.

The water passes by an electromagnetic volumetric flowmeter Conault, model OPTIFLUX6000 from range 0 to 12 m/s and accuracy of 0.5%, and then is directed to the mixer and test section. The rotation speed pump and flowrate in the test section are controlled by a frequency inverter CWF10.

The air is supplied by a compressed air-line available in the laboratory, and its pressure is adjusted to gauge pressure of 276 kPa by a pressure regulator valve, and then passes by thermal mass flowmeters model GFM 37 with measuring range from 0 to 40 L/min and accuracy 0.5%.

The experiments are performed for conditions close to the atmospheric pressure and ambient temperature. The teste section consists in a 10.8 m horizontal acrylic pipe, with internal and external diameters of 44.6 and 50.0 mm, respectively. The measurement section was installed 7.35 m downstream the mixer section aiming to allow flow pattern development, and to reduce effects of inlet and outlet sections.

The velocity profile was determined by using the non-intrusive technique Particle Image Velocimetry PIV, Fig.2 b, available in the research group. The system is composed by laser Big Sky Ultra PIV 120 at 532nm type Nd:YAG and camera Dantec FlowSense 4M Mk2, with maximum resolution of 2048x2048 pixels. The tracer consisted in polymeric particles with mean diameter between 20 and 50 µm and possesses Rodhamin B dye, that is a fluorescent substance for excitation with wavelength of 532 nm, and emits in the wavelength range 520nm to 570nm.

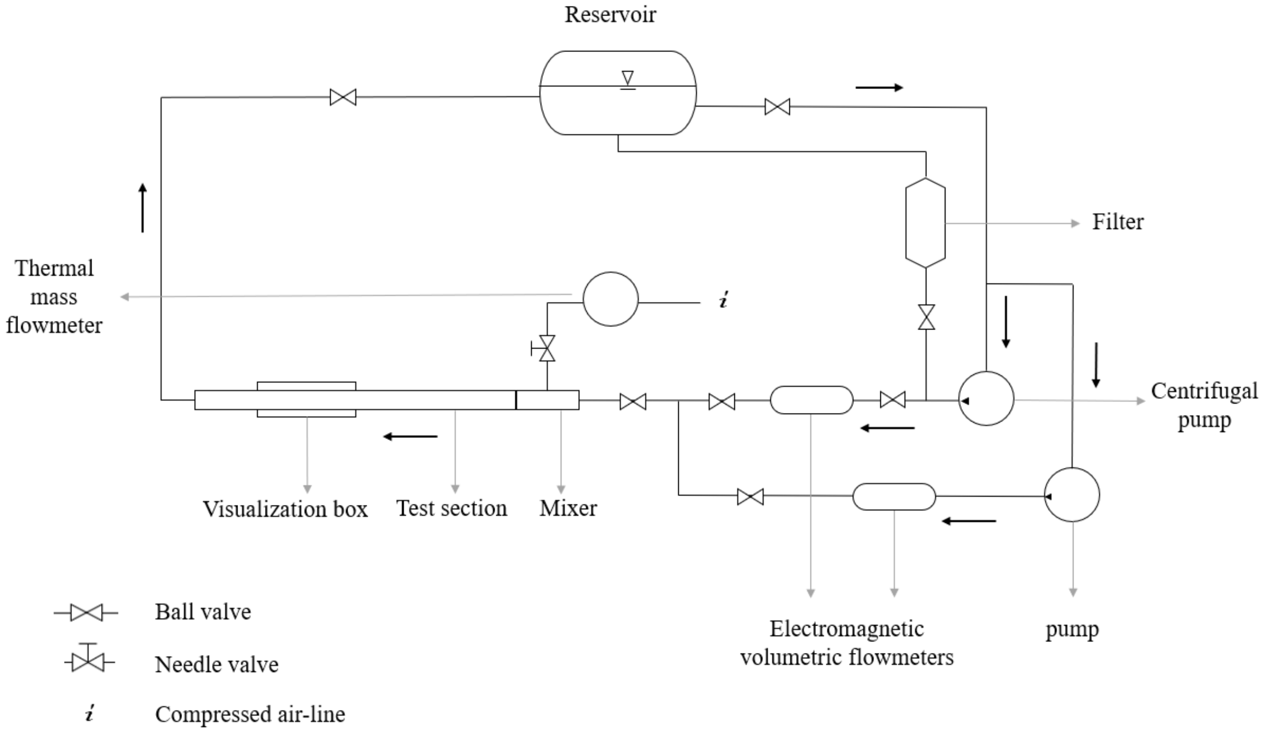

Figure 1. Circuit of tests.

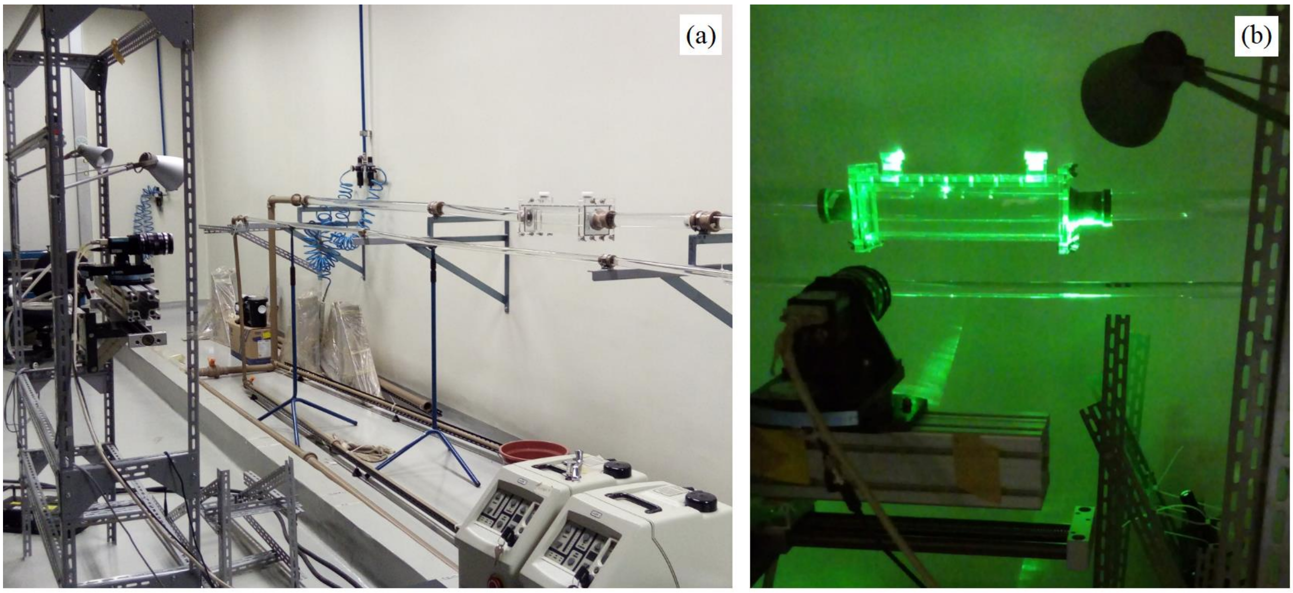

Figure 2. (a) Tests section and visualization box installed (b) visualization box and camera.

3.2 Experimental methodology

The tracer particles are added to the liquid in the reservoir, with concentration of approximately 15ml of particle per 100L of water. The centrifugal pump of large capacity is turned on by adjusting the frequency of excitation by the frequency inverter. The water superficial velocity across the acrylic section was adjusted with the help of the electromagnetic flowmeter, with flow rate of 80L/min to 90L/min, corresponding to superficial velocities between 0,853 to 0,960 m/s. After few minutes the centrifugal of large capacity pump is turned off. This process at high flowrate is performed aiming to homogeneous mixing the particles to the liquid and distribute them in the circuit.

Then, the lower capacity pump is turned on to impose a flow pattern stratified, which requires reduced liquid and gas flow. Simultaneously, the air flowrate is manually adjusted by needle valves in order to obtain the smooth and wavy stratified flows.

According to the operating principle of PIV system, the particles dispersed in the fluid reflect the light emitted by the laser in a range of microseconds between the two pulses, as well as emit light according to the characteristics of the fluorescent dye. The PIV system is controlled by the computer that start the acquisition of images with pulsed laser source positioned below of visualization box. The captured images are stored in the computer to be post-processed by the Dynamic Studio software.

4. RESULTS AND DISCUSSION

4.1 Velocity profiles

Fig.3 depicts the velocity field in the central plane for the liquid phase during smooth stratified flow, with gas and liquid superficial velocities of 0,0747 and 0,0769 m/s, respectively. It can be concluded according to this figure that the velocity profile agrees with expected, with velocity tending to null value close to the lower tube. Additionally, the liquid velocity increases with distance from the tube wall up to the maximum value in the interface, as shown in Fig. 3.

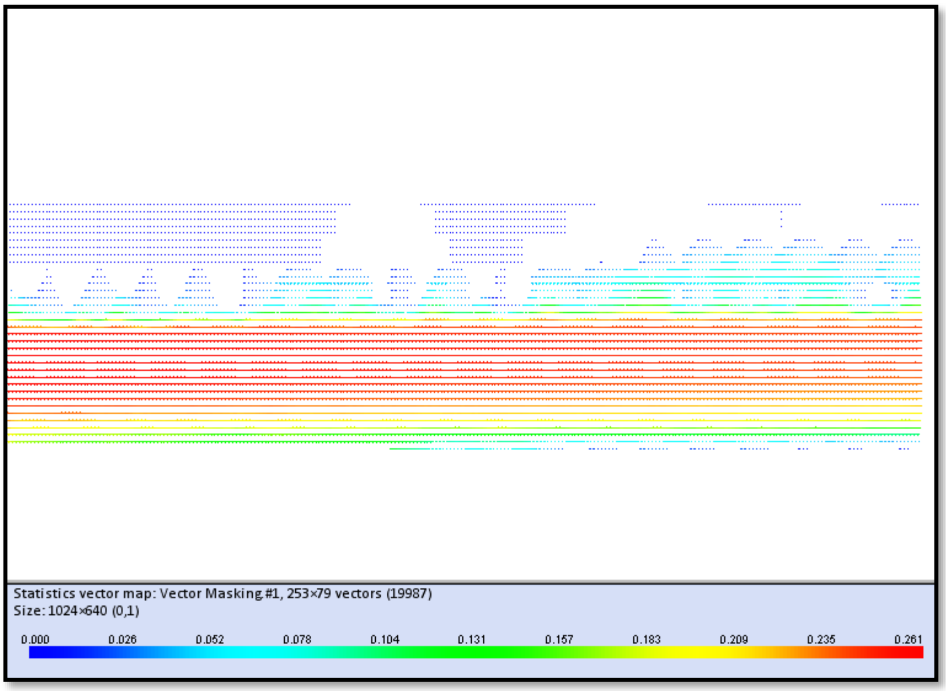

Figure 3. velocity profile in the smooth stratified flow was obtained by Dantec Dynamic Studio program.

The velocity profile along the channel vertical coordinate has been evaluated based on the velocity results such as depicted in Fig. 3, by considering mean values along a short length along channel axis. The results of the velocity tests for each group were evaluated from the analysis of the standard deviation of velocity along axial direction for a given vertical coordinate, assuming maximum lengths that correspond to standard deviation smaller than 10% of the mean value as threshold to consider as invariable. Based on this analysis, groups of 20 elements were considered in the axial direction to evaluate the corresponding velocity profile.

Fig. 4 illustrates the velocity profiles for the liquid phase in the smooth stratified flow, which was obtained with 5 group of 1000 images each for gas and liquid superficial velocities of 0,0747 and 0,0769 m/s, respectively. According to this figure, the velocity profiles agrees with the expected, with null value close to the channel wall in the lower part of the section, and increases with distance from the solid wall. Close to the interface, the experimental results are not reliable due to scattering of the laser in the liquid-gas interface, which might compromise the PIV method.

Based on these results, it is possible to estimate the shear stress profile along the liquid film, which is presented in the next section.

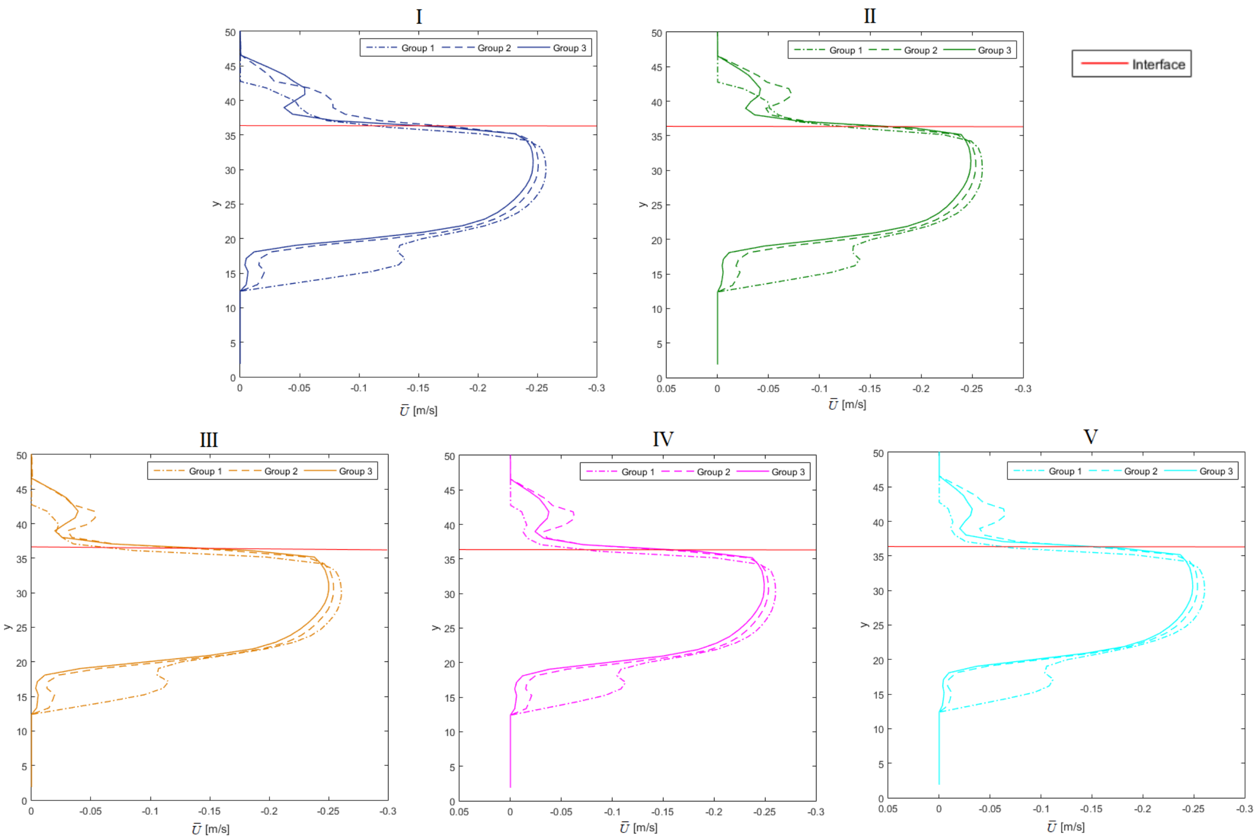

Figure 4. Velocity profiles obtained with 5 groups of 1000 images.

4.2 Shear stress

Figure 5 depicts the shear stress profile along the vertical coordinate comprising the viscous and turbulent components. The total shear stress that was estimated by mean velocity profile, presents maximum values close to the tube wall due parcel of viscous shear stress is dominant. According to White (1974), the total shear stress tensor can be written as:

$$\tau_{xy} = \mu\left(\frac{\partial \bar{U}}{\partial y} + \frac{\partial \bar{V}}{\partial x}\right) - \rho\overline{u'v'} \tag{1}$$

where the first term corresponds to the viscous shear stress and the second term corresponds to the Reynolds turbulent stress tensor. Figure 5 depicts the experimental results for shear stress evaluated according to this method, whereas the derivatives were estimated adopting a finite difference method. According to this table, the experimental results for shear stress also agrees with expected, with maximum values close to the channel wall and to the gas-liquid interface, and smaller values away from these interfaces.

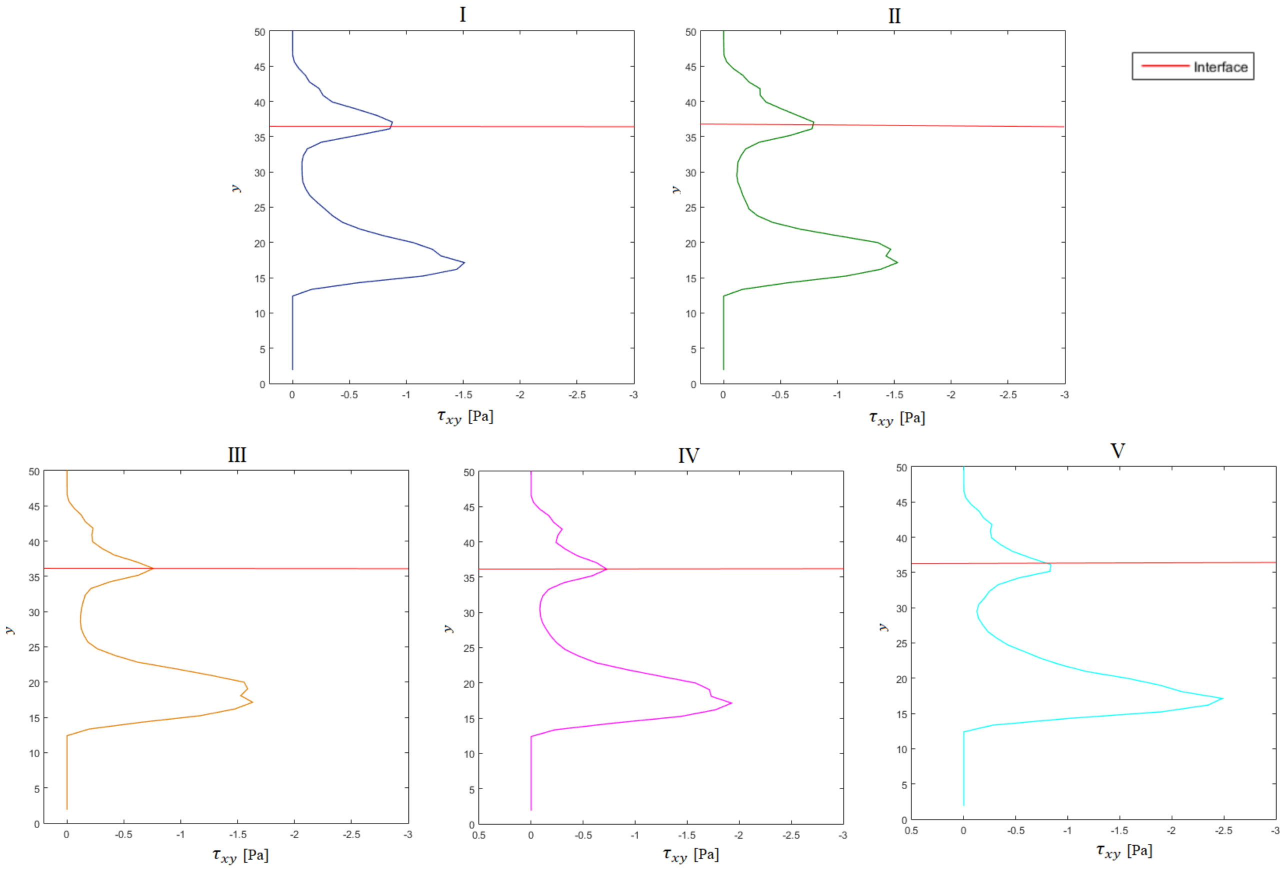

Figure 5. Shear stress profile through the tube.

5. CONCLUSIONS

This study presents an experimental investigation focused on determination of velocity profile and shear stress for the liquid phase during stratified flow. The following conclusions can be addressed:

- The Particle Image Velocimetry method showed to be reasonable for experimental determination of velocity profile for the liquid phase during stratified flow.
- A post processing analysis for estimation of liquid shear stress has been performed, and the experimental results agrees with the expected, with higher values close to the solid-liquid and gas-liquid interfaces, and small value away from these interfaces. It is expected that these results, when validated, can contribute to the understanding of pressure drop during stratified flow patterns.

The present study is currently under development, and the next steps comprise analysis of experimental results for wavy stratified flow.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

The authors Marta Lemos, Maria Helena Farias, Douglas Garcia, Eving Silva and Fabio Toshio Kanizawa are the only responsible for the printed material included in this paper.